



Research Paper / Makale

Permanent Magnet Flux Switching Torque Performance Indicator

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Abstract: Flux switching machine (FSM) offer advantages such as rotor robustness and simple driving circuit compared to competing machine. This paper attempts to process the torque, volume and current information from 35 latest Permanent Magnet (PM) FSM publication into a standardized Torque Performance Indicator (TPI), which are torque density, torque constant, torque constant density and torque-magnet ratio. The distribution median shows that torque density, torque constant, torque constant density and torque-magnet ratio are 23.24kNm/m³, 0.43Nm/A, 0.616Nkm/Am³ and 30.79Nm/kg respectively. Among many design variation, outer rotor configuration produces good values as overall in the TPI. This information can be used to guide the machine designer to compare and compete based on the standardized TPI.

Keywords: Flux switching machine, Machine design, Torque density, Torque constant, Finite element

Kalıcı Mıknatıs Akısı Anahtarlama Tork Performansı Gösterge

Öz: Flux switching machine (FSM), rakip makineye kıyasla rotor sağlamlığı ve basit sürüş devresi gibi avantajlar sunar. Bu makale, tork, hacim ve akım bilgilerini en son 35 Permanent Magnet (PM) FSM yayınından, tork yoğunluğu, tork sabiti, tork sabit yoğunluğu ve tork-mıknatıs oranı olan standartlaştırılmış bir Torque Performance Indicator (TPI) işlemeye çalışmaktadır. Dağılım medyanı, tork yoğunluğu, tork sabiti, tork sabit yoğunluğu ve tork-mıknatıs oranının sırasıyla 23.24kNm / m³, 0.43Nm / A, 0.616Nkm / Am³ ve 30.79Nm / kg olduğunu göstermektedir. Birçok tasarım varyasyonu arasında, dış rotor konfigürasyonu genel olarak TPI'da olduğu gibi iyi değerler üretir. Bu bilgi, makine tasarımcısına standartlaştırılmış TPI'ya göre karşılaştırma ve rekabet etme konusunda rehberlik etmek için kullanılabilir.

Anahtar Kelimeler: Akı anahtarlama makinesi; Makine tasarımı; Tork yoğunluğu; Tork sabiti; Sonlu elemanlar

1. Introduction

Electric car deployment has been growing rapidly over the past ten years, with the global stock of electric passenger cars passing 5 million in 2018, an increase of 63% from the previous year. About 45% of electric cars on the road in 2018 were in China compared to 39% in 2017. In comparison, Europe accounted for 24% of the global fleet, just 2% above the United States [1, 2]. In order to achieve all these market objectives, all these items related to vehicle electric drives, which include electric machines, power electronics and their respective cooling system should be improved further. Electrical machine design advancement has become competitive in recent years. According to the standard IEC line motor (IEC 60034-30-1) released in 2014, the motor efficiency level has

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Bu makaleye atıf yapmak için

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included the forth efficiency level which is IE4 namely super premium efficiency that categorize the maximum achievable efficiency to be 96.7% [3]. Nevertheless, this number hold true only for conventional type of motor that uses direct on-line operation mainly synchronous and induction motor. For EV application, the efficiency target is 94% for its drive system [4]. Meanwhile, DC motor are equally important and useful to get its due attention because of the main source of power to drive the motor is direct current that can be supplied by battery. This feature enables the motor to be used in electrical vehicle application. (Figure 1) shows the classification of dc electrical machine in commutation type and field excitation [5].

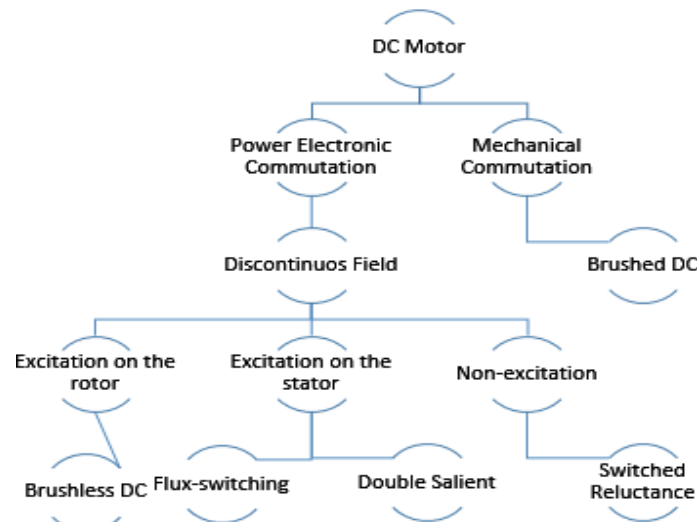


Figure 1. Classification of dc electrical machine

Flux switching machine (FSM) offer advantages such as rotor robustness and simple driving circuit compared to competing machine. It requires a simple converter to drive the motor and inherit robust rotor structure such in switch reluctance machine. This paper attempts to process the information from 35 latest PMFSM publication into a standard Torque Performance Indicator (TPI), which are torque density, torque constant, torque constant density and torque-magnet ratio. Among many design variation, outer rotor configuration performed reasonably well based on the overall TPI. This information can be used to guide the machine designer to compare and compete based on the standardized TPI.

2. Working Principle of Permanent Magnet Flux Switching Machine

Flux switching motor is a combination of the switched reluctance motor and the inductor alternator. The first PSM motor was discovered in [6] in 1999. The motivation of this invention is to introduce simplicity in motor design and power electronics controller. In a later study [7], due to rapid design evolution in the automotive industry, mechanically driven auxiliaries were being substituted by electrically driven equipment for example water pumps, steering system, heating, ventilation and air-conditioning. Brushless dc motor, induction motor and switched reluctance motor were chosen, but it comes with a relatively costly power electronic motor drive. To understand its working principle, a flux switching motor is drawn in (Figure 2a). This motor is a configuration of 8 stator slot-4rotor pole structure. The field winding coil 1 is feed with direct current continuously while the armature winding supplies DC according to the position of the rotor.

The circuit diagram for this motor is illustrated in (Figure 2b). It is important to make aware of these two figures to reflect the robustness of the motor structure and the simplicity of the motor driving circuit. (Figure 3a and 3b) illustrate the flux path at two rotor's positions. Alignment of the rotor poles and stator poles can be considered as the reference position ($\Theta_r = 0^\circ$).

The flux enters from stator pole through the rotor pole and exit at the aligned stator pole 90° from the initial point. The flux path is created by the DC field F- and armature coil 2 A+ when switch S1 is at the “ON” state.

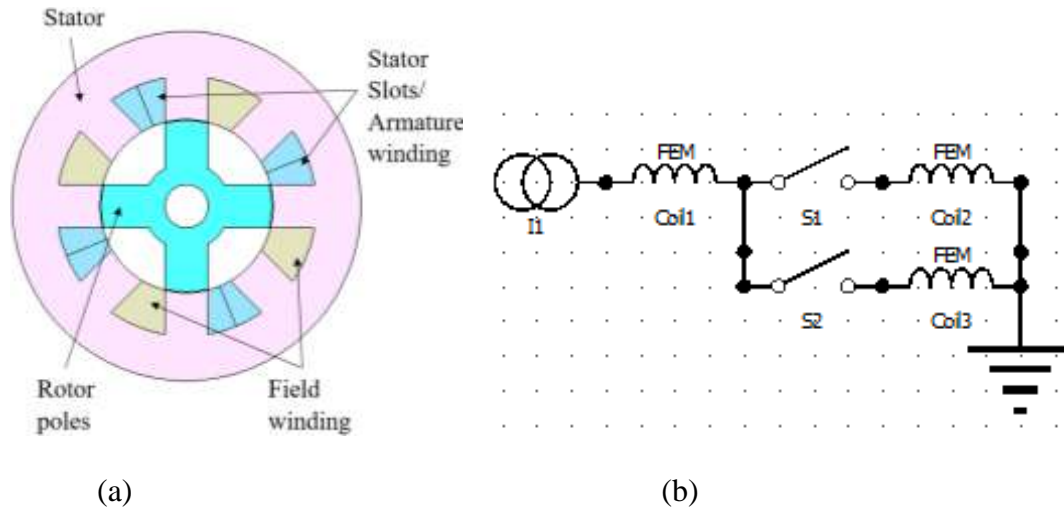


Figure 2. Flux switching machine structure and circuit diagram for flux switching motor 8/4 stator slot-rotor pole.

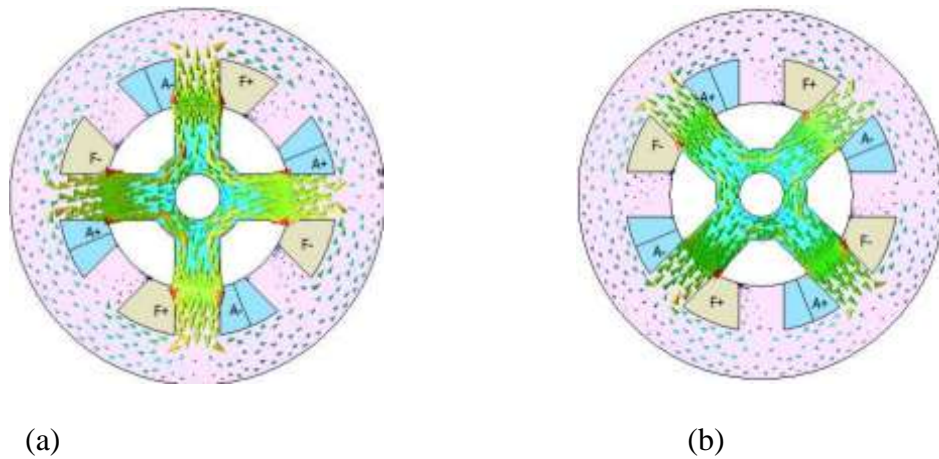


Figure 3. Flux direction at rotor position (a) $\Theta_{r1} = 0^\circ$ S1 ON/S2 OFF (b) $(\Theta_{r2} = 90^\circ)$ S1 OFF/S2 ON

At the same instant, with the field winding having a constant direct current, the polarity of armature coil 3 turns to receive the direct current (F+, a-) by switching S1 to “OFF” state and switch S2 to “ON” state. In this state, the resultant flux path is to anti-clockwise direction; hence the rotor moves anti-clockwise to the next align pole ($\Theta_{r2} = 90^\circ$). This state change continues to switch the flux path by controlling the switch S1 and S2 through the bifilar winding, thereby the resultant magnetic field attracts the rotor and the continuous rotation of the motor is maintained.

3. PMFSM Standardized TPI Procedure and Result

3.1. Torque Density and Torque Constant

Design criteria of any electrical machine mainly focus on output power and torque. However, each topology may not give the optimum torque due to its size and application. PMFSM can be categorized into four main structure, that is an inner rotor, outer rotor, double rotor and double stator. In order to understand its torque performance, power or torque output are insufficient.

Thirty-five latest publications that consist of a variety of topology were studied. Information such as motor volume, magnet volume, current, output torque from these publications were used to calculate torque density T_d , and torque constant T_c . This information should be able to assist the researcher in PMFSM to explore other regions of T_c and T_d . Even though it is unfair to group every design due to its specific application, comparing future PMFSM research against this data might be useful in general. T_d , is defined as the ratio of torque to the volume of the motor in SI units Nm/m^3 . (T_d) is calculated by using the equation 1.

$$T_d = \frac{T}{V_{ol}} \tag{1}$$

(T_c) is defined as the ratio of torque to the value of the peak armature current in Nm/A as shown in the following equation 2 [8].

$$T_c = \frac{T}{I_{ar}} \tag{2}$$

Some of the motor volume data were not available in the previous research paper. Hence, the geometry was redrawn according to the figure provided in the research paper. The total volume of the machine was calculated by subtracting air-gap volume between the rotor pole and shaft. The PM density used in calculating PM weight or volume is set to $7550kg/m^3$ which is NdFeb type having a strength of the magnetic field B_r between 1 to 1.4 T. The largest volume found from 35 PMFSM designs is around $0.006m^3$. Figure 4 shows the torque density versus motor volume graph and Figure 5 shows the torque constant versus motor volume.

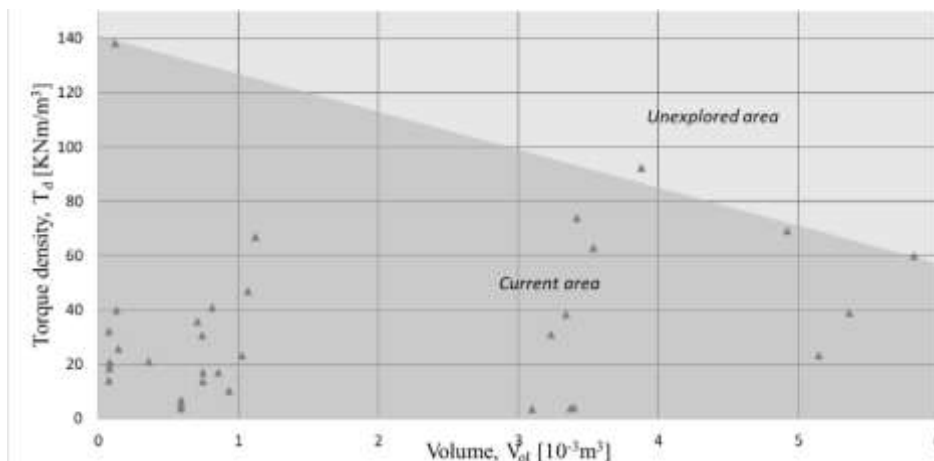


Figure 4. Torque density (T_d) versus volume (Vol) from past PMFSM publication.

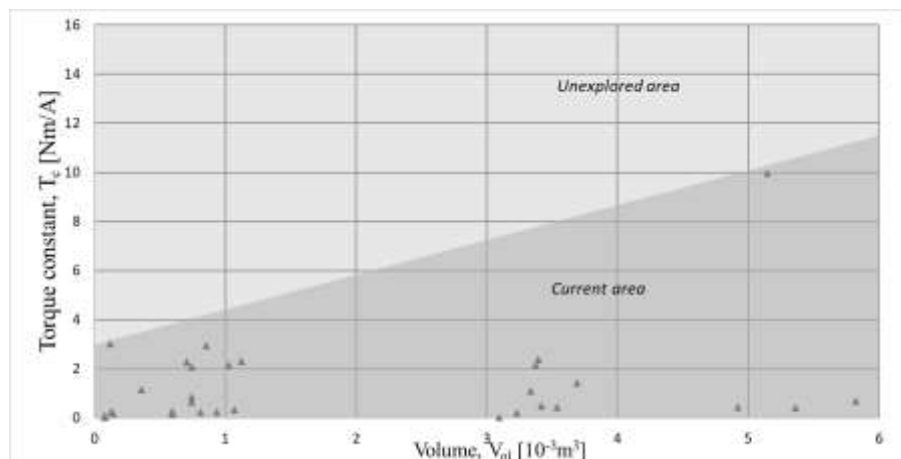


Figure 5. Torque constant (T_c) versus volume (Vol) from past PMFSM publication

3.2. Torque Constant Density and Torque-Magnet Ratio

Based on (Figure 4) and (Figure 5), limited design has been performed in the volume region around 0.002 m^3 . A correctly size PMFSM could enable significant improvements in performance and cost, thus representing a critical knowledge that every designer should take into consideration [9]. The highest torque density, T_d is 138.11 KNm/m^3 while torque constant, T_c is 9.967 Nm/A . T_d is the ratio of mechanical torque over the physical size of an active part in the motor. At the same time, T_c is the ratio of electrical energy (current) being converted into mechanical energy. Although the PMFSM in the literature currently has high T_d and T_c , portable application demands higher T_d and T_c .

To obtain alternative TPI, both parameters of T_d and T_c are rearranged as shown in equation 3 (T_{cd}). The fourth TPI is proposed in equation 4 (T_{mag}). This TPI accommodate the weight of PM which might be useful in the cost sensitive application. T_{cd} and T_{mag} are calculated and presented in the graph in (Figure 6) and (Figure 7).

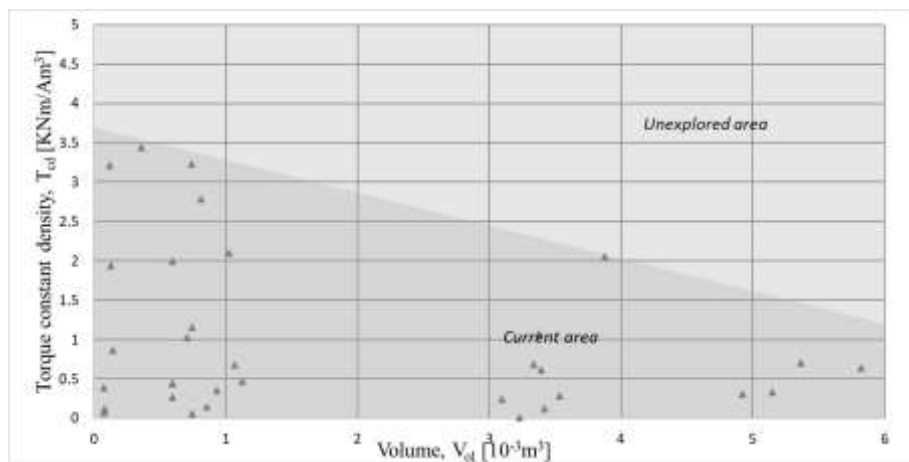


Figure 6. Torque constant density (T_{cd}) versus volume (Vol) from past PMFSM publication.

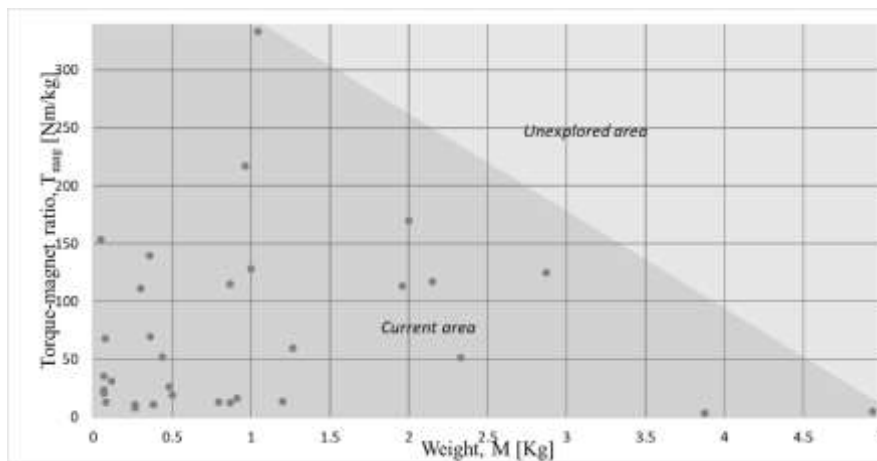


Figure 7. Torque-magnet ratio (T_{mag}) versus magnet weight, (M) from past PMFSM publication.

$$T_{cd} = \frac{T}{Vol \cdot I \cdot ar} \tag{3}$$

$$T_{mag} = \frac{T}{Mag_{kg}} \tag{4}$$

3.3. Torque Normal Distribution

The distribution of each torque index are shown below (Figure 8-11). (Table 1) summarizes six best PMFSM design for each TPI. Motor output and the percentage of cogging torque were extracted as additional information for the reader. 3-phase outer rotor 12S-22P possess the highest torque density of 138KNm/m³ but the torque-magnet ratio is low [10], and its torque ripple is 20%. On the other hand, 3-phase outer rotor 24S-14P produce high torque density and torque to magnet ratio but low torque constant and torque constant density which is suitable in various direct drive application [11–14]. Partition stator 12S-10P produce a good overall torque parameter for inner-rotor structure [15]. High torque constant density produce by 3-phase outer rotor 12S-22P is a trade-off of low torque to magnet ratio [16]. Full-pitch winding 12S-7P PMFSM is also listed in the table mainly because its inherit good winding factor [17]. Unfortunately, this design suffers a considerable unbalance magnetic field.

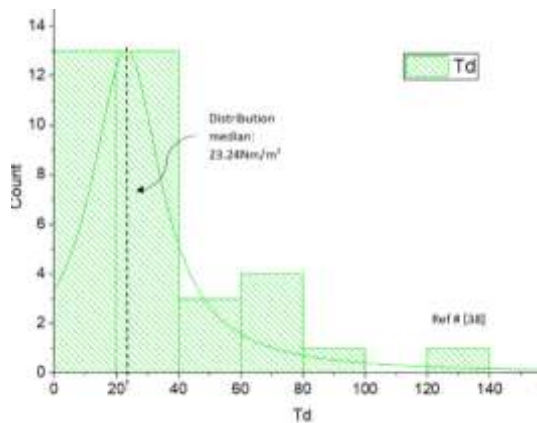


Figure 8. T_d distribution of 35 designs

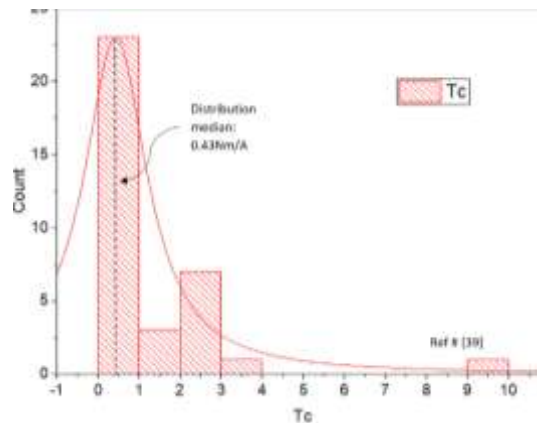


Figure 9. T_c distribution of 35 designs.

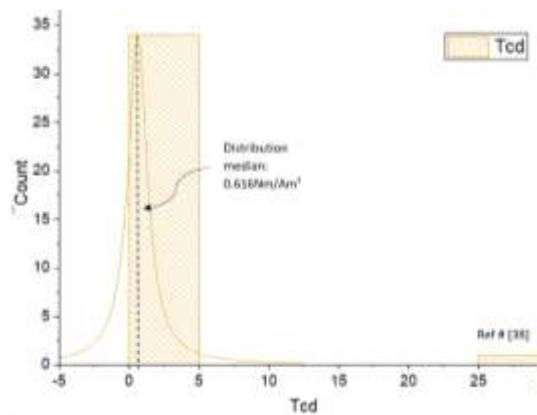


Figure 10. T_{cd} distribution of 35 designs.

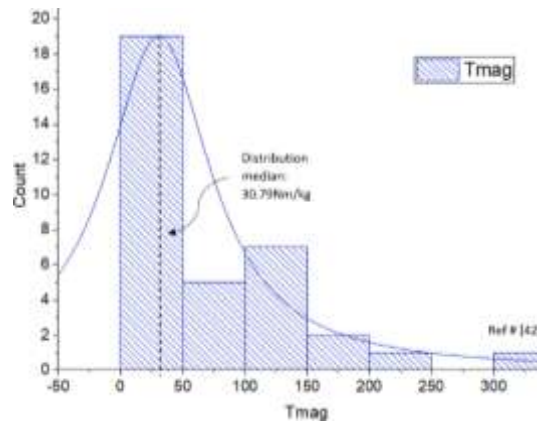


Figure 11. T_{mag} distribution of 35 designs.

Table 1. Calculated torque parameter of six best PMFSM design

Motor Type	Vol 10 ³ m ³	T _d [KNm/m ³]	T _c [Nm/A]	T _{cd} [KNm/A.m ³]	T _{mag} [Nm/kg]	*T _{cog} [%]	Power (kW)	Ref.
Outer rotor	0.119	<u>138.116</u>	3.015	<u>25.412</u>	13.658	20	4.13	[10]
Outer rotor	5.362	38.975	0.410	0.076	<u>217.200</u>	4	30	[16]
Outer rotor	5.822	59.878	0.684	0.117	<u>333.647</u>	6	45	[14]
Outer rotor	4.919	69.095	0.429	0.087	169.912	1.5	1.5	[11]
Double stator	3.878	<u>92.318</u>	1.432	0.388	124.825	8	45	[15]
Full Pitch	0.855	17.050	2.939	3.437	<u>16.013</u>	3	**0.9	[17]

*Percentage ratio between cogging torque and average torque

**Mechanical output

This state of the art graph in (Figure 4-6) in general do not show linearity between torque parameter and volume like expected in other machines [18, 19]. The main reason was the ratio of total volume to the magnet volume in a smaller motor is high hence elevated the torque produced thus it can vary widely over the full spectrum of the motor available [20]. Figure. 4(b) shows that the magnet weight is distributed randomly and at a maximum of near 5 kg. In general, the amount of output torque increase as either magnetic loading increase or electric loading increase. Designer should note that as magnetic loading increase, the flux weakening capability may become less effective. In terms of the economic evaluation of using PM machine over a non-PM machine, 25% of motor utilization over a year is enough to have 2.5 years of payback period [21]. The remaining data which were used to generate the graph were listed in (Table 2).

Table 2. Calculated torque parameter of the remaining 29 PMFSM design.

Structure highlight	Vol.	T_d [KNm/m ³]	T_c [Nm/A]	T_{cd} [KNm/A.m ³]	T_{mag} [Nm/kg]	Ref.
Conventional	0.078	18.486	0.048	0.616	20.714	[22]
Conventional	0.077	32.216	0.082	1.074	35.286	[22]
Conventional	0.080	20.573	0.055	0.686	23.571	[22]
Conventional	0.081	20.460	0.055	0.682	23.571	[22]
Conventional	0.075	13.903	0.035	0.473	13.000	[23]
Axial laminated	0.359	20.909	1.154	3.217	153.583	[24]
Five-Phase Modular	3.393	3.978	2.376	0.700	3.486	[25]
Five-Phase Modular	3.373	3.617	2.147	0.637	3.150	[25]
3-Phase Outer rotor	3.336	38.365	1.109	0.332	128.000	[26]
3-Phase Outer rotor	1.067	46.855	0.329	0.308	139.471	[27]
3-Phase Outer rotor	1.123	66.801	2.301	2.048	59.323	[28]
3-Phase Outer rotor	5.146	23.243	9.967	1.937	51.362	[11]
Partition stator	0.129	39.908	0.257	1.995	68.015	[29]
Partition stator double layer	0.594	6.823	0.265	0.447	10.631	[30]
Partition stator single layer	0.594	6.722	0.261	0.440	10.473	[30]
Partition stator doub. layer	0.594	3.622	0.157	0.264	8.062	[30]
Partition stator single layer	0.594	4.852	0.210	0.353	10.799	[30]
Alternate radial and circumferential flux	0.933	10.182	0.224	0.240	19.000	[31]
Conventional	3.095	3.425	0.021	0.007	12.212	[32]
3 -phase	3.232	30.923	0.196	0.061	115.150	[32]
V-shape magnet	0.745	13.739	0.858	1.152	12.868	[33]
Multi-tooth	0.745	17.056	0.643	0.863	26.324	[33]
Segmented magnet	0.141	25.647	0.144	1.026	30.792	[34]
Partition Rotor	0.706	35.554	2.282	3.232	69.405	[35]
Partition Rotor	0.742	30.610	2.064	2.783	51.838	[35]
Modular rotor	0.812	41.016	0.230	0.283	111.000	[36]
Segment. stator	3.535	62.886	0.437	0.124	113.418	[37]
Segment. stator	3.417	73.825	0.495	0.145	117.473	[38]
V-shape magnet inner stator	1.024	23.099	2.150	2.100	4.789	[39]

2. Conclusions

The data gathered to generate the graph are based on 35 designed published by the previous researcher specifically in PMFSM. The distribution median of torque density, torque constant, torque constant density and torque-magnet ratio are 23.24kNm/m³, 0.43Nm/A, 0.616kNm/Am³ and 30.79Nm/kg respectively. Considering the presented information, the readers achieve enough understanding of the weaknesses and strong points of each PMFSM topology and its contribution towards the standardized indicator. According to this study, 4 out of 6 best design which yield the highest TPI are PMFSM using outer rotor structure. Each TPI value highlight torque ratio against

machine volume, armature current and magnet ratio. This information can be used to guide the machine designer to compare and compete based on the standardized values. There are still several factors that need to be investigated to improve the TPI calculation such as air gap, efficiency and torque ripple. Due to the limited information given in the literature, these parameters are not included in this paper.

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Authors' contributions

HA and SE carried out the study and wrote up the article. Both authors read and approved the final manuscript.

Conflict of Interest

The authors confirm that there is no conflict of interest to declare for this publication.

Refereneces

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